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STATISTICAL ANALYSIS OF THE BURST TEST RESULTS ON RUPTURE PRESSURE PANELS

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The statistical analysis of the sample data obtained from burst tests on the rupture pressure panels to be installed at all units of Pickering Nuclear Generation Station is presented. The analysis concentrates on determining (i) whether all tested panels burst within the designed pressure interval; and (ii) whether the panels will operate within the design criteria in case of a loss-of-coolant accident or a main-steam-line-break accident. The results of the analysis indicate that the above questions can be answered affirmatively.

1. INTRODUCTION

A statistical analysis of the test results of the rupture panels to be installed at all units of Pickering 'A' Nuclear Generation Station[1] was carried out. The objective of the analysis was to: (i) determine whether the burst pressure of all tested panels was between 12.5 kpa and 20 kpa; (ii) determine whether the panels will operate adequately in case of a loss-of-coolant accident (LOCA) or in case of a main-steam-line-break accident (MSLB). In case of a LOCA, the reactor building (RB) will be pressurized at a rate between 1 kpa/min to 11 kpa/s and the panels are expected to burst when the differential pressure between the RB and the pressure relief duct is between 12.5 kpa to 17.5 kpa. In case of a MSLB, the RB will be pressurized at a rate between 11 kpa/s to 24 kpa/s and the panels are expected to burst when the differential pressure is between 12.5 and 20 kpa.

2. DATA

The panels were manufactured by Process Equipment Limited. They were produced in four batches or lots, each of approximately 130 panels. During the production process the manufacturer implemented a quality assurance (QA) program to control the quality of the panels. At the end of the production of each lot an additional sampling program was implemented to determine the acceptance of the remaining panels in the lot[2].

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The QA program consisted of bursting every 10^{th} panel of each lot as they came out of production. The acceptance program for each lot consisted of bursting about 20 randomly selected panels after they have been exposed to one of six different stress conditions. The stress conditions were applied to simulate the conditions the rupture panels will be exposed to during the normal operation of the unit. The six stress conditions resulted from a combination of three types of treatments and a bursting rate. The treatments were (i) an application of pressure to the panel, denoted as leakage (L); (ii) an application of a temperature transient (T); and (iii) an application of a pressure transient (P). The exposures were either at the front face of the panel (F) or at the reverse face (R). The bursting rate were slow (SB), medium (MB) or fast (FB). The six conditions were:

A: LF, MB
B: LR, LF, MB
C1: TF, LF, MB
C2: TF, LF, TR, LR, SB
C3: TF, PR, LR, PF, LF, SB
D: SB

(The condition of the panels during the QA test is denoted as ST).

During the acceptance sample the panels were divided in two groups. Each of these groups was tested according to the 210-A or the 210-B type of test. In the 210-A tests, the panels were subject to medium or slow bursts. In the 210-B tests, the panels were subject to fast bursts. The type of test (TID), the condition the panel was exposed to (CID), the bursting pressure (BP), and the pressurizing rate (PR) were recorded for each panel tested. These values are given in Table 1 together with the lot identification number (LOT) and the panel identification number (PANEL).

3. ANALYSIS AND RESULTS

Table 2 gives the maximum and minimum values of BP and PR for each type of test. An inspection of the BP values indicates that panels tested at low PR (TID = A) burst between 13.90 and 17.14 kpa, and panels tested at high PR (ie. TID = B) burst between 13.29 and 18.60 kpa. Furthermore, all tested panels burst within 13.29 and 19.55 Kpa. This implies that all panels burst within the designed BP interval.

To study if the panels will operate properly in case of an accident, it is necessary to analyze the effect that CID, LOT and PR have on the BP values. This will allow the calculation of a prediction confidence interval for the values of BP expected in case of an accident. Note that the values of PR provide more accurate information of the type of test carried out on a given panel than the information coded in the TID variable. For this reason this variable is not included in the following analysis.

An analysis of covariance ANCOVA[3] was used to carry out the analysis. The model can be written in the form

$$BP_{ij} = \mu + \beta_P PR_{ij} + \beta_C CID_{ij} + \beta_{PC} PR^{*}CID_{ij} + \beta_L LOT_i + \epsilon_{ij} \qquad (1)$$

where μ represent the overall mean of the data; the indices ij refer to the j^{th} panel of the i^{th} lot, $i = 1, 2, 3, 4$; $j = 1, 2, ..., n_i$; the β's are the coefficients of the model; PR*CID is an interaction factor to take into account possible differences in the effect of the PR on the BP due to the different CID's; and the ϵ's represent the errors in the model, assumed to be inde-

pendent and normally distributed with zero mean and σ^2 variance. The term $\beta_{PC}CID_{ij}$ can be interpreted as the change in slope of the linear relation between PR and BP due to the effect of CID. The term $\beta_L LOT_i$ takes into account the possible differences between panels from different lots.

The model of Equation (1) was fitted using the GLM procedure of SAS[4]. The results are given in five parts in Table 3. Part 1 presents the overall significance of the model. Part 2 presents the tests of significance for each of the variables: the values associated with the Type I SS assume that only the variables previously listed in the table are in the model; the values associated with the Type III SS assume that all the listed variables are in the model. Part 3 lists the estimates of the intercept and the slope of the linear relations between PR and BP for panels tested under each of the CID values; it also gives the probability value for testing the significance of the parameter. Part 4 gives the results for testing the significance of the difference between the adjusted BP values of one lot (or batch) versus the average of the adjusted BP values of the other 3 lots. Finally, part 5 lists the estimate values of the parameters of the model.

The results can be summarized as follows.

(i) The BP values fitted by the model reduces by 66% the total variation of the observed BP values.

(ii) There is no overall lot effect in the model. This implies that all panels can be considered to be homogeneous.

(iii) The relationship between BP and PR depends on the treatment applied to the panels prior to bursting. In CID = B and CID = C3 the relationship seems to have a negative (although not significant) slope; for the other CID values the slope is positive. This is shown in figures 1 to 7 which present a scatter plot of the observed data together with the fitted values and 95% predicted confidence bounds for each observation.

To determine whether or not the rupture panels will meet the design conditions in case of LOCA or MSLB accidents, a set of predicted BP values was calculated for each accident. These are given in Table 4. As can be seen from the table, the set consisted of expected BP values, together with their standard deviations (SIGMA), and 95% and 99% predictive confidence intervals. These were calculated at the lowest and highest PR values expected in the accident, for each CID value (except QA) and assuming an average lot effect. The predictions given in the rows denoted AV were calculated assuming an average CID effect. Three rows associated with LOCA are marked with an "*": CID = A, B and C1. These correspond to projections of BP values outside the observed PR interval and may not be valid, but are included for completeness. It is observed that all the expected BP values are within the design region.

The predictive intervals indicate the range of differential pressure values at which the majority of panels will burst (assuming they operate at conditions simulated by the CID values and are pressurized at the given PR values). For example, if it can be assumed that an average CID value represent the conditions to which the panels will be exposed to in the reactor building, then, at the worst condition of a LOCA accident (PR = 11 kpa/s), 99% of the panels are expected to burst when the differential pressure between the RB and the pressure relief duct is between 13.59 kpa and 17.77 kpa.

For LOCA, the upper confidence bounds seem much larger than the design value. However, note that for the worst condition predicted by the model, namely CID = B and PR = 1 kpa/min, about 76%[1] of the panel will burst at pressure differences between 12.5 to 17.5 kpa. Therefore, the unavailability of the rupture system (ie. the probability that less than 10 out of 29 panels burst) is 3.8×10^{-7}, much less than the design requirements. For MSLB, even the 99% confidence limits are within the design values, which implies that the design requirements are satisfied.

4. CONCLUSIONS

Based on the results of the analysis, the following conclusions can be made.

(i) The tested panels met the acceptance sampling requirements specified by the acceptance sampling plan.

(ii) A model to investigate the relationship between PR and BP of the panels was fitted to the data. Estimated BP values, together with 95% and 99% predictive intervals were calculated. It was found that all the estimated values are within the design requirements. It was also found that for MSLB all the bounds of the confidence intervals are within the design values. For LOCA, not all bounds are within the design values, but even in the worst situation, the availability values of the rupture panels system exceeded the design requirements.

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1. At the stated conditions, the model predicts that the panels will burst at an average pressure of 16.70 kpa with a standard deviation of 1.13 kpa (see Table 4). From here the probability of the interval [12.5, 17.5] is estimated to be 76%.

TABLE 1

PANEL SAMPLE DATA

LOT	PANEL	TYPE TEST	COND TEST	PR Rate (kpa/s)	BRST PR (kpa)
1	11	A	A	4.930	15.737
1	39	A	B	13.950	16.541
1	33	A	C2	0.019	15.387
1	59	A	C3	0.019	13.901
1	37	A	C1	16.440	13.990
1	57	A	D	0.013	17.135
1	45	A	D	0.014	15.737
1	58	A	D	0.014	16.261
1	60	B	A	25.040	17.625
1	52	B	B	24.730	16.471
1	84	B	C2	21.930	16.051
1	78	B	C1	24.950	14.548
1	73	B	C3	47.120	13.289
1	42	B	D	25.190	17.660
1	70	B	D	25.220	17.450
1	48	B	D	29.380	16.401
1	46	B	D	30.610	17.695
1	101	QA	ST	19.500	18.884
1	102	QA	ST	43.110	19.548
1	93	QA	ST	43.630	17.800
1	30	QA	ST	55.550	17.661
1	12	QA	ST	55.630	16.856
1	40	QA	ST	56.440	17.940
1	51	QA	ST	57.200	16.716
1	61	QA	ST	59.700	18.149
1	71	QA	ST	62.970	19.268
1	82	QA	ST	62.970	19.268
1	91	QA	ST	65.380	19.199
1	83	QA	ST	65.430	19.373
2	127	A	A	19.700	14.617
2	105	A	B	1.910	16.436
2	69	A	C3	0.017	14.897
2	39	A	C2	0.018	15.125
2	15	A	C1	9.340	14.897
2	7	A	C1	9.730	15.527
2	104	A	D	0.018	15.000
2	89	A	D	0.018	15.701
2	118	A	D	0.019	15.037
2	119	B	A	59.170	16.331
2	111	B	B	20.320	16.296
2	81	B	C3	20.610	14.757
2	56	B	C2	20.990	15.806
2	23	B	C1	31.740	16.506
2	32	B	C1	34.460	16.436
2	113	B	D	35.780	18.464
2	116	B	D	36.280	17.415

TABLE 1 (Cont.)

PANEL SAMPLE DATA

LOT	PANEL	TYPE TEST	COND TEST	PR Rate (kpa/s)	BRST PR (kpa)
2	123	B	D	58.320	18.604
2	10	QA	ST	1.610	15.590
2	20	QA	ST	2.400	15.140
2	50	QA	ST	2.500	15.320
2	30	QA	ST	3.100	15.180
2	70	QA	ST	3.300	15.040
2	60	QA	ST	3.440	14.790
2	40	QA	ST	3.450	15.600
2	90	QA	ST	3.540	15.910
2	130	QA	ST	3.570	15.240
2	120	QA	ST	3.690	15.140
2	80	QA	ST	3.870	15.840
2	100	QA	ST	3.990	15.280
2	110	QA	ST	4.090	15.320
3	109	A	C3	0.017	15.704
3	87	A	C2	0.018	14.428
3	2	A	C1	4.140	16.365
3	11	A	C1	9.660	15.666
3	29	A	C1	10.170	15.107
3	16	A	C1	10.330	15.281
3	44	A	D	0.017	14.900
3	65	A	D	0.017	14.603
3	94	A	D	0.017	14.65[illegible]
3	99	B	C2	11.630	15.526
3	119	B	C3	13.160	15.176
3	51	B	C1	13.200	16.086
3	33	B	C1	13.290	14.967
3	75	B	C1	13.510	15.596
3	69	B	C1	13.890	15.666
3	113	B	C3	32.458	16.716
3	105	B	C2	33.308	16.821
3	84	B	C1	47.904	17.485
3	126	B	D	12.450	15.596
3	123	B	D	12.800	15.946
3	103	B	D	13.730	15.386
3	57	B	D	19.098	17.905
3	90	QA	ST	12.620	15.456
3	40	QA	ST	12.630	14.687
3	50	QA	ST	12.680	15.386
3	100	QA	ST	12.680	15.981
3	20	QA	ST	12.780	15.736
3	120	QA	ST	12.820	15.526
3	110	QA	ST	12.840	15.736
3	80	QA	ST	12.940	15.386
3	30	QA	ST	12.960	15.072
3	70	QA	ST	13.370	15.631
3	60	QA	ST	13.660	15.596

TABLE 1 (Cont.)

PANEL SAMPLE DATA

LOT	PANEL	TYPE TEST	COND TEST	PR Rate (kpa/s)	BRST PR (kpa)
3	10	QA	ST	25.600	14.897
4	14	B	A	28.890	15.316
4	6	B	A	31.064	15.526
4	35	B	B	27.910	15.351
4	29	B	B	28.090	16.296
4	55	B	C3	27.970	14.967
4	51	B	C2	28.830	16.575
4	74	B	D	26.690	17.485
4	83	B	D	27.980	15.387
4	80	QA	ST	25.890	16.580
4	60	QA	ST	26.650	16.930
4	90	QA	ST	26.850	17.450
4	100	QA	ST	26.870	16.930
4	70	QA	ST	27.040	16.230
4	50	QA	ST	27.090	17.070
4	40	QA	ST	27.750	17.200
4	30	QA	ST	28.320	16.850
4	10	QA	ST	31.100	18.040
4	20	QA	ST	33.060	17.520

TABLE 2

PANEL SAMPLE DATA
Maximum and Mininum Values for Bursting Pressure (BP) and Pressurizing Rates (PR) by Type of Test (TID) and Condition of the Test (CID)

		ALL			
		PR (kpa/s)		BP (kpa)	
TID	CID	MIN	MAX	MIN	MAX
A	A	4.93	19.70	14.62	15.74
	B	1.91	13.95	16.44	16.54
	C1	4.14	16.44	13.99	16.36
	C2	0.02	0.02	14.43	15.39
	C3	0.02	0.02	13.90	15.70
	D	0.01	0.02	14.60	17.14
	ALL	0.01	19.70	13.90	17.14
B	CID				
	A	25.04	59.17	15.32	17.62
	B	20.32	28.09	15.35	16.47
	C1	13.20	47.90	14.55	17.48
	C2	11.63	33.31	15.53	16.82
	C3	13.16	47.12	13.29	16.72
	D	12.45	58.32	15.39	18.60
	ALL	11.63	59.17	13.29	18.60
QA	CID				
	ST	1.61	65.43	14.69	19.55
	ALL	1.61	65.43	14.69	19.55
ALL	CID				
	A	4.93	59.17	14.62	17.62
	B	1.91	28.09	15.35	16.54
	C1	4.14	47.90	13.99	17.48
	C2	0.02	33.31	14.43	16.82
	C3	0.02	47.12	13.29	16.72
	D	0.01	58.32	14.60	18.60
	ST	1.61	65.43	14.69	19.55
	ALL	0.01	65.43	13.29	19.55

TABLE 3

SAMPLE PANEL DATA
ANCOVA: Linear PR by CID

General Linear Models Procedure
Class Level Information

Class	Levels	Values
CID	7	A B C1 C2 C3 D ST
LOT	4	1 2 3 4
TID	3	A B QA

Number of observations in data set = 112

Dependent Variable: BP

PART 1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	16	121.2406899	7.5775431	11.63	0.0001
Error	95	61.8991436	0.6515699		
Corrected Total	111	183.1398335			

R-Square	C.V.	Root MSE	BP Mean
0.662012	4.999912	0.807199	16.1442589

PART 2

Source	DF	Type I SS	Mean Square	F Value	Pr > F
PR	1	85.32518893	85.32518893	130.95	0.0001
CID	6	20.61996278	3.43666046	5.27	0.0001
PR*CID	6	14.04674159	2.34112360	3.59	0.0030
LOT	3	1.24879655	0.41626552	0.64	0.5918

Source	DF	Type III SS	Mean Square	F Value	Pr > F
PR	1	6.75088509	6.75088509	10.36	0.0018
CID	6	3.18240410	0.53040068	0.81	0.5616
PR*CID	6	12.51947435	2.08657906	3.20	0.0066
LOT	3	1.24879655	0.41626552	0.64	0.5918

TABLE 3 (Cont.)

SAMPLE PANEL DATA
ANCOVA: Linear PR by CID

PART 3

Parameter		Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
Intcpt	CID=A	15.32054515	22.83	0.0001	0.67096346
Linear PR	CID=A	0.01722334	0.83	0.4065	0.02065601
Intcpt	CID=B	16.70378389	21.23	0.0001	0.78666582
Linear PR	CID=B	-0.02697148	-0.73	0.4645	0.03672719
Intcpt	CID=C1	15.03590766	38.25	0.0001	0.39313563
Linear PR	CID=C1	0.03831525	2.11	0.0371	0.01812403
Intcpt	CID=C2	14.97698315	34.11	0.0001	0.43912296
Linear PR	CID=C2	0.05266631	2.33	0.0218	0.02258667
Intcpt	CID=C3	15.14939564	35.71	0.0001	0.42418277
Linear PR	CID=C3	-0.01091368	-0.62	0.5347	0.01751453
Intcpt	CID=D	15.45967233	61.90	0.0001	0.24977071
Linear PR	CID=D	0.05835434	5.40	0.0001	0.01080907
Intcpt	CID=ST	15.24754983	70.60	0.0001	0.21597490
Linear PR	CID=ST	0.05233475	7.10	0.0001	0.00736941

PART 4

Parameter	Estimate	T for H0: Parameter=0	Pr > |T|	Std Error of Estimate
LOT 1 vs OTHERS	0.22745623	1.05	0.2961	0.21648451
LOT 2 vs OTHERS	-0.12579732	-0.62	0.5369	0.20298323
LOT 3 vs OTHERS	-0.21435462	-1.13	0.2599	0.18911058
LOT 4 vs OTHERS	0.11269571	0.50	0.6154	0.22357056

TABLE 3 (Cont.)

SAMPLE PANEL DATA
ANCOVA: Linear PR by CID

PART 5

INTERCEPT		15.33207161 B	52.75	0.0001	0.29067682
PR		0.05233475 B	7.10	0.0001	0.00736941
CID	A	0.07299532 B	0.10	0.9201	0.72602594
	B	1.45623406 B	1.81	0.0733	0.80403037
	C1	-0.21164218 B	-0.49	0.6274	0.43456667
	C2	-0.27056668 B	-0.56	0.5782	0.48495241
	C3	-0.09815419 B	-0.21	0.8330	0.46413338
	D	0.21212250 B	0.64	0.5205	0.32890027
	ST	0.00000000 B	.	.	.
PR*CID	A	-0.03511140 B	-1.54	0.1261	0.02275402
	B	-0.07930622 B	-2.15	0.0340	0.03686906
	C1	-0.01401949 B	-0.72	0.4743	0.01951500
	C2	0.00033156 B	0.01	0.9889	0.02371735
	C3	-0.06324842 B	-3.41	0.0009	0.01852443
	D	0.00601959 B	0.46	0.6470	0.01310376
	ST	0.00000000 B	.	.	.
LOT	1	0.08607039 B	0.33	0.7423	0.26099766
	2	-0.17886977 B	-0.67	0.5070	0.26857167
	3	-0.24528774 B	-0.93	0.3562	0.26454411
	4	0.00000000 B	.	.	.

NOTE: The X'X matrix has been found to be singular and a generalized inverse was used to solve the normal equations. Estimates followed by the letter 'B' are biased, and are not unique estimators of the parameters.

TABLE 4

Predictive Intervals for LOCA

CID	PR(kpa/s)		ESTIMATE	SIGMA	L95	U95	L99	U99
A	1/60	*	15.32	1.05	13.26	17.38	12.64	18.00**
A	11		15.51	0.94	13.66	17.36	13.11	17.91**
B	1/60	*	16.70	1.13	14.49	18.91**	13.83	19.58**
B	11		16.41	0.93	14.59	18.22**	14.05	18.77**
C1	1/60	*	15.04	0.90	13.28	16.80	12.75	17.33
C1	11		15.46	0.85	13.80	17.12	13.30	17.62**
C2	1/60		14.98	0.92	13.18	16.78	12.63	17.32
C2	11		15.56	0.86	13.87	17.24	13.36	17.75**
C3	1/60		15.15	0.91	13.36	16.94	12.82	17.47
C3	11		15.03	0.87	13.33	16.72	12.82	17.24
D	1/60		15.46	0.84	13.80	17.12	13.31	17.62**
D	11		16.10	0.83	14.48	17.72**	13.99	18.21**
AV	1/60		15.44	0.84	13.80	17.08	13.31	17.57
AV	11		15.68	0.82	14.07	17.28	13.59	17.77**

* Indicate predictions outside the observed range of values and so the predictions may not be valid.

** Indicate values outside the designed BP interval.

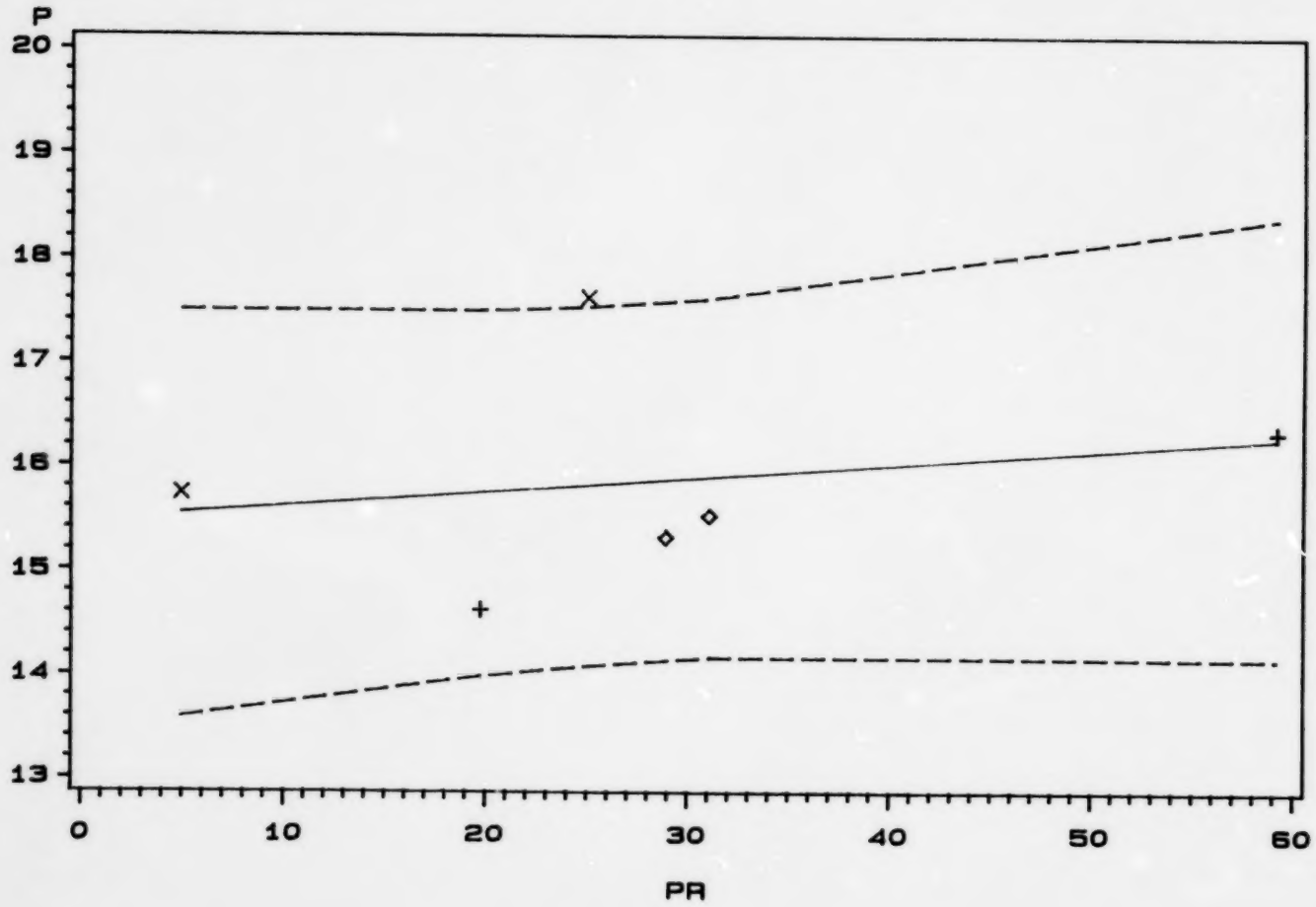
Predictive Intevals for MSLB

CID	PR(kpa/s)	ESTIMATE	SIGMA	L95	U95	L99	U99
A	11	15.51	0.94	13.66	17.36	13.11	17.91
B	11	16.41	0.93	14.59	18.22	14.05	18.77
A	24	15.73	0.88	14.02	17.45	13.50	17.97
B	11	16.41	0.93	14.59	18.22	14.05	18.77
B	24	16.06	0.89	14.31	17.80	13.79	18.32
C1	11	15.46	0.85	13.80	17.12	13.30	17.62
C1	24	15.96	0.84	14.30	17.61	13.80	18.11
C2	11	15.56	0.86	13.87	17.24	13.36	17.75
C2	24	16.24	0.88	14.51	17.97	13.99	18.49
C3	11	15.03	0.87	13.33	16.72	12.82	17.24
C3	24	14.89	0.86	13.20	16.58	12.69	17.09
D	11	16.10	0.83	14.48	17.72	13.99	18.21
D	24	16.86	0.83	15.23	18.49	14.74	18.98
AV	11	15.68	0.82	14.07	17.28	13.59	17.77
AV	24	15.96	0.82	14.35	17.56	13.87	18.04

PANEL SAMPLE DATA

COV–ANOVA: Linear PR by CID

CID-A



X: Lot 1 +: Lot 2 ▽: Lot 3 ◇: Lot 4

Observed and Fitted values with 95% predicted confidence bounds

Figure 1

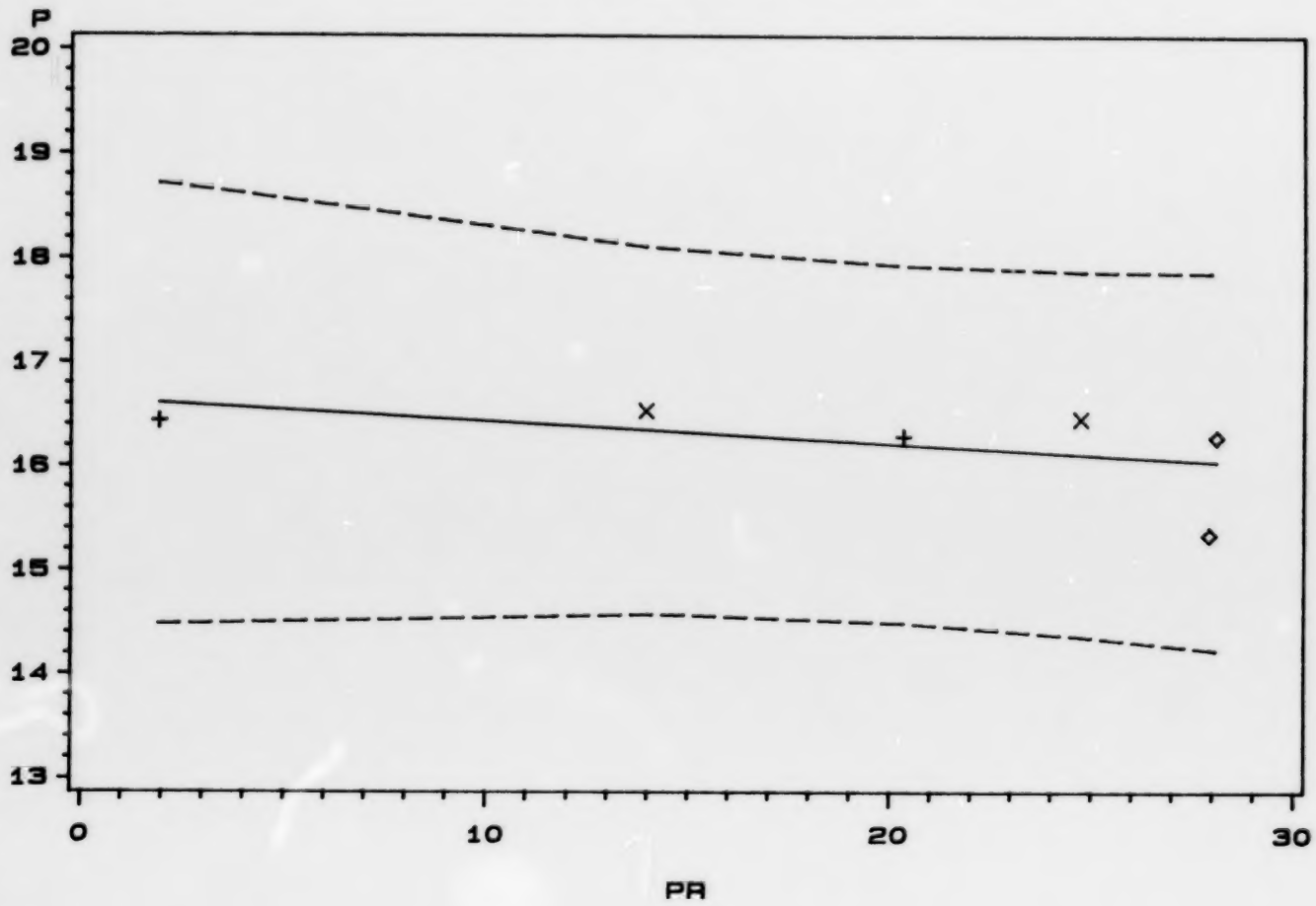
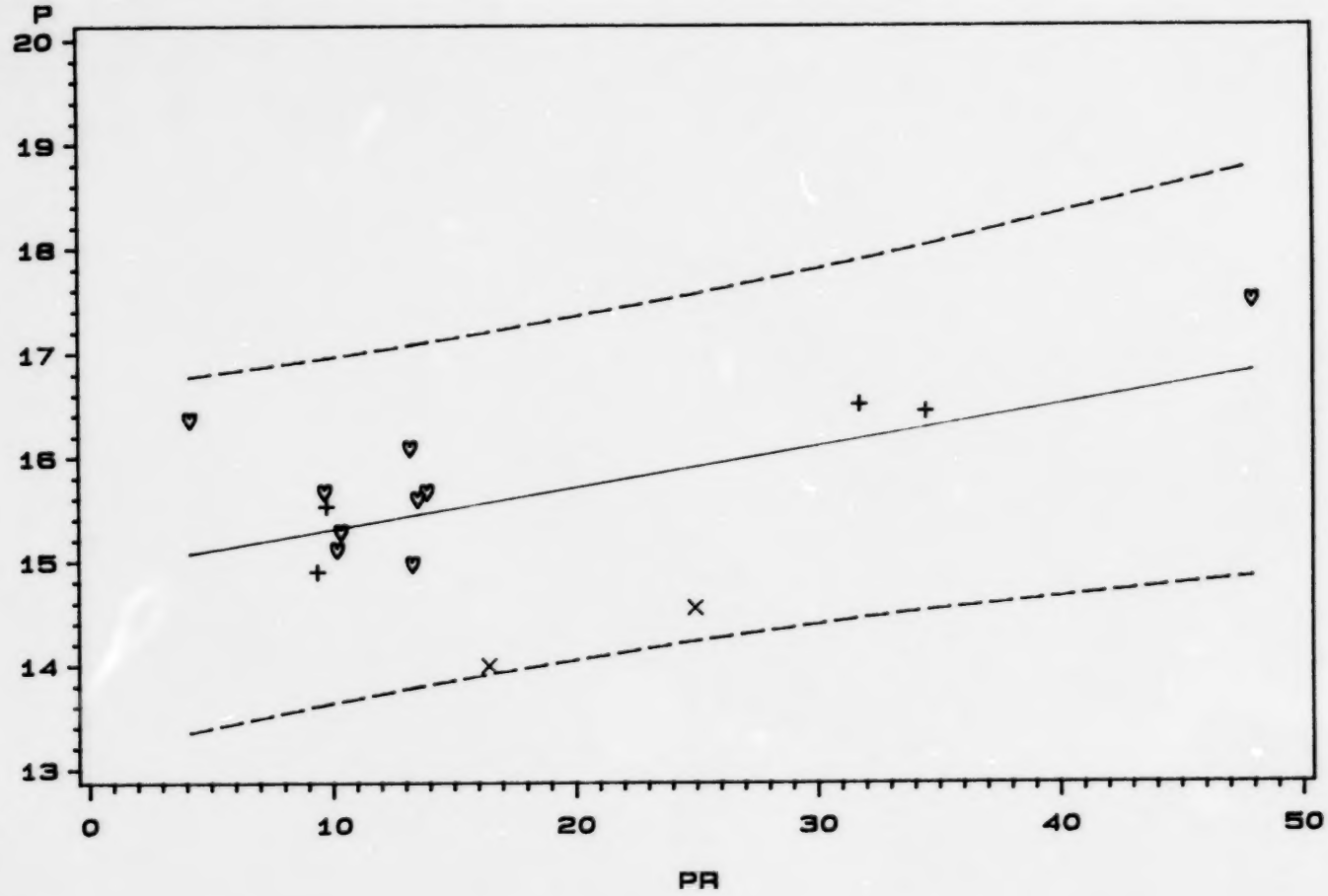

PANEL SAMPLE DATA
COV—ANOVA: Linear PR by CID
CID-B
P
20
19
18
17
16
15
14
13
0
10
20
30
PR
X: Lot 1 +: Lot 2 ▽: Lot 3 ◇: Lot 4
Observed and Fitted values with 95% predicted confidence bounds

Figure 2

PANEL SAMPLE DATA

COV–ANOVA: Linear PR by CID

CID=C1



X: Lot 1 +: Lot 2 ♡: Lot 3 : Lot 4

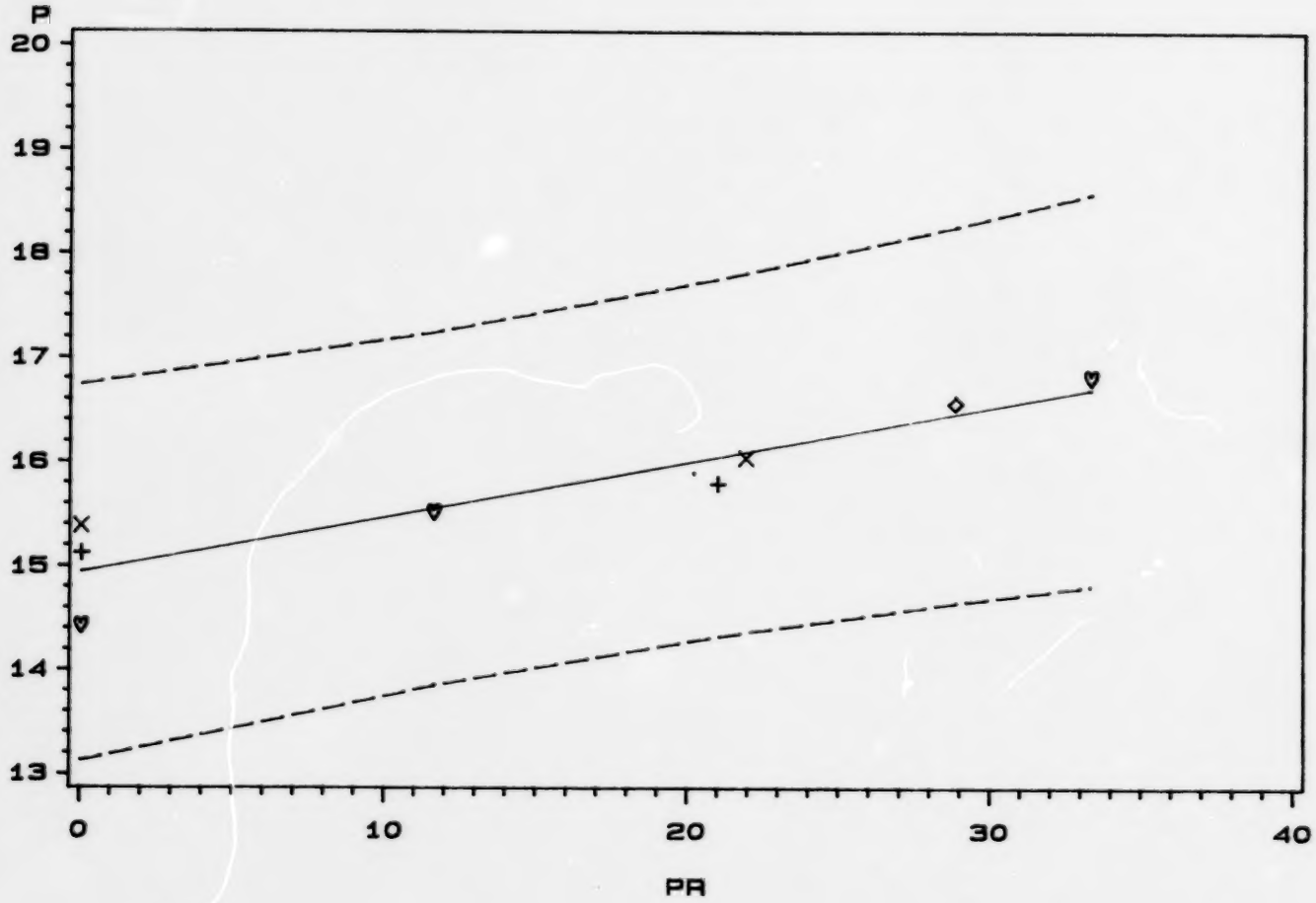
Observed and Fitted values with 95% predicted confidence bounds

Figure 3

PANEL SAMPLE DATA

COV–ANOVA: Linear PR by CID

CID=C2



X: Lot 1 +: Lot 2 ▽: Lot 3 ◇: Lot 4

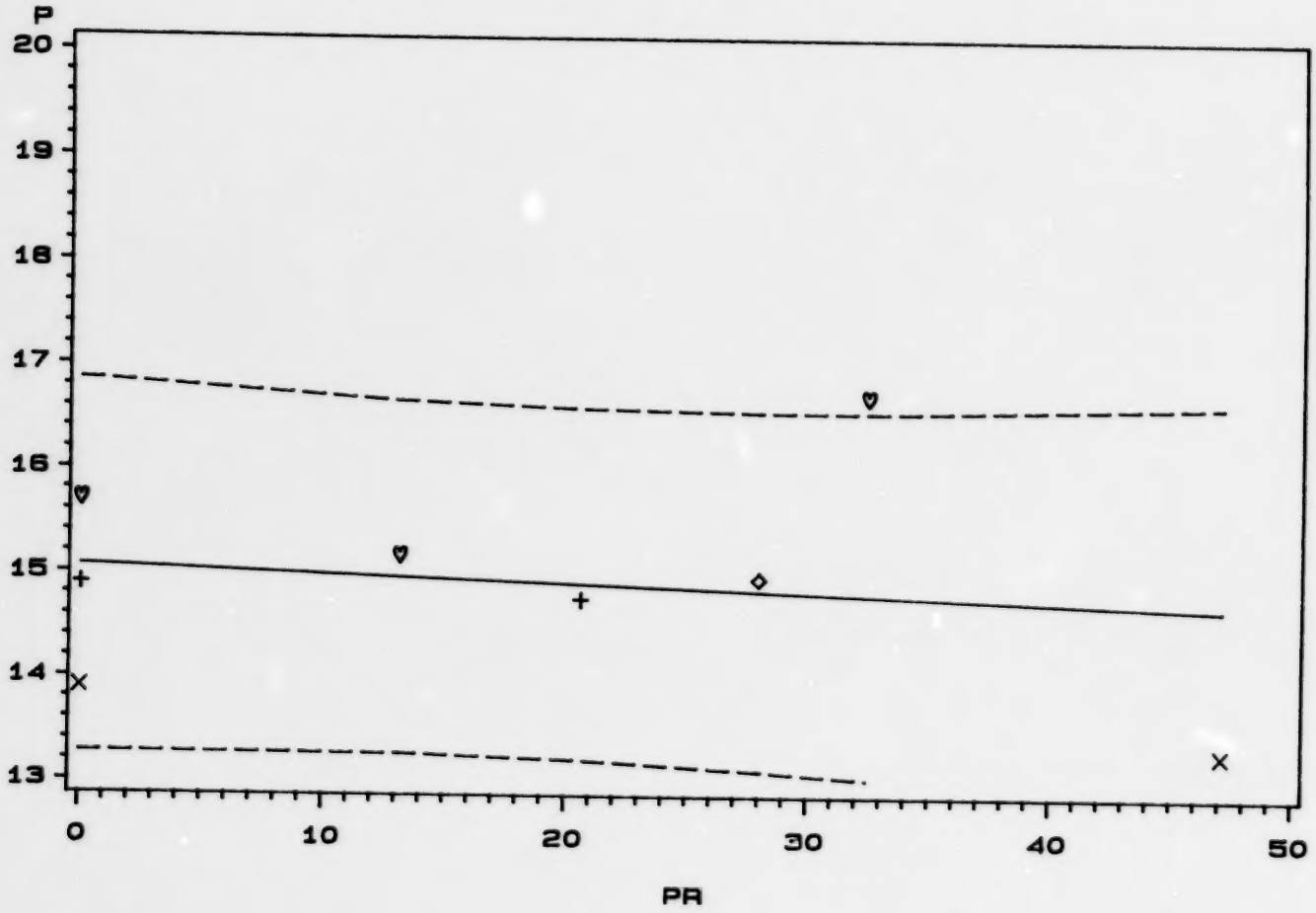
Observed and Fitted values with 95% predicted confidence bounds

Figure 4

PANEL SAMPLE DATA

COV–ANOVA: Linear PR by CID

CID-C3



X: Lot 1 +: Lot 2 ♡: Lot 3 ◇: Lot 4

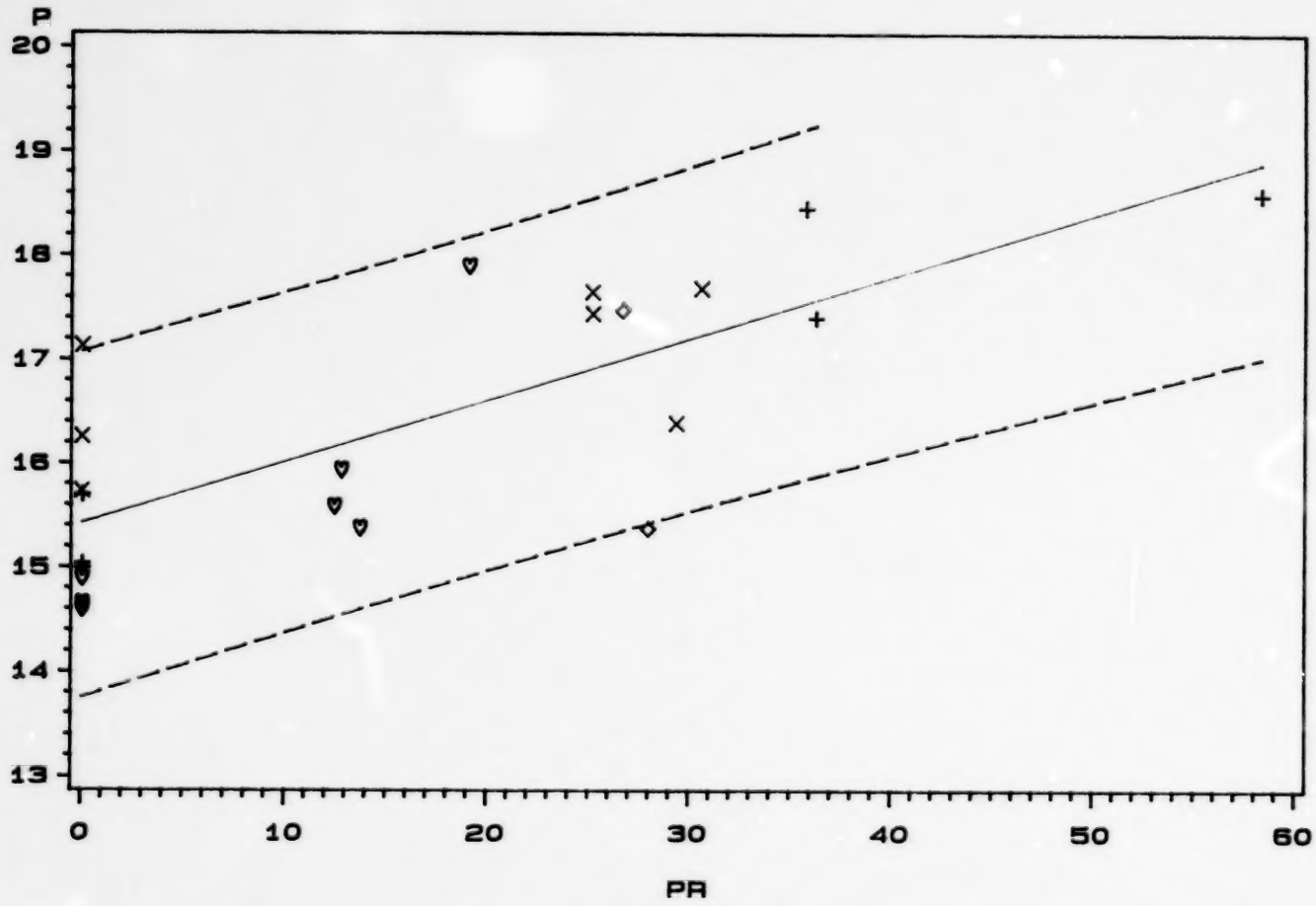
Observed and Fitted values with 95% predicted confidence bounds

Figure 5

PANEL SAMPLE DATA

COV–ANOVA: Linear PR by CID

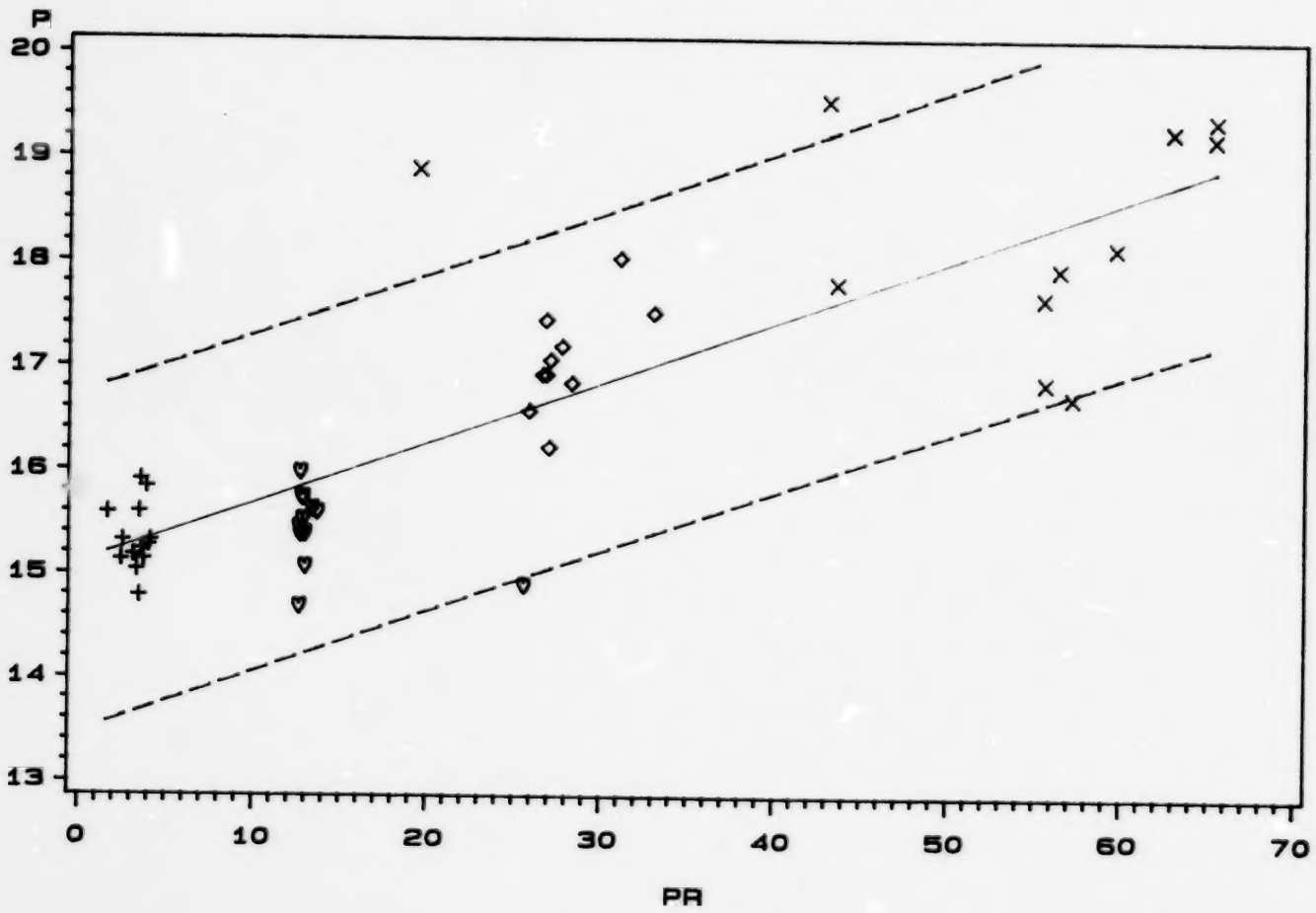
CID=D



X: Lot 1 +: Lot 2 ▽: Lot 3 ◇: Lot 4

Observed and Fitted values with 95% predicted confidence bounds

Figure 6



X: Lot 1 +: Lot 2 ▽: Lot 3 ◇: Lot 4

Observed and Fitted values with 95% predicted confidence bounds

Figure 7